Dark photon and dark Z mediated B meson decays

Ahmed Rashed

Shippensburg University of Pennsylvania

Quantum Universe Attract Workshop, DESY 2025

Published for SISSA by Springer

Received: October 31, 2022
Revised: March 1, 2023
Accepted: March 1, 2023
Published: March 16, 2023

Dark photon and dark Z mediated B meson decays

Alakabha Datta,[a] A. Hammad,[b] Danny Marfatia,[c] Lopamudra Mukherjee[a] and Ahmed Rashed[d]

Introduction

- Flavor-Changing Neutral Currents (FCNCs) such as $f \to \grave{f} N$ are strongly suppressed in the Standard Model for any neutral state N.

Source of suppression	Effect
No tree-level FCNCs	eliminates large contributions
Loop suppression	loop factor
GIM mechanism	destructive cancellations between quark generations
Small CKM factors	small mixing angles reduce amplitude

- Therefore, FCNC processes are rare and provide strong probes of new physics.
- The goal of our work is to utilize FCNC processes in setting constraints on the parameter space of a new physics model.

Models

Model: Dark $U(1)_D$ model, with the dark photon/dark Z mass between 10MeV and 2 GeV.

We study three different cases of the light Z_D model as specified below.

- **Case A:** This is the dark photon and dark Z model described by

$$\mathcal{L}_D^{\text{em}} \supset e\varepsilon Z_D^\mu J_\mu^{\text{em}} - ie\varepsilon\,[[Z_D W^+ W^-]] \qquad \mathcal{L}_D^Z \supset \frac{g}{\cos\theta_W}\varepsilon_Z Z_D^\mu J_\mu^Z - ig\cos\theta_W \varepsilon_Z\,[[Z_D W^+ W^-]]$$

with the kinetic (ε) and mass (ε_Z) mixing parameters.

- **Case B:** A muonphilic Z_D in which Case A is extended with an additional direct interaction of the dark Z with muons

$$\mathcal{L}_D^Z \supset g_D^\mu \bar{\mu}\gamma_\alpha \mu Z_D^\alpha$$

- **Case C:** Case A is extended with additional direct interactions of the dark Z with both electrons and muons

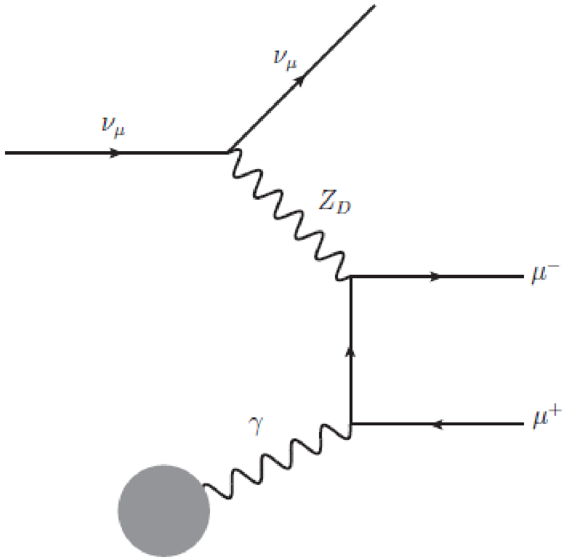
$$\mathcal{L}_D^Z \supset g_D^e \bar{e}\gamma_\alpha e Z_D^\alpha + g_D^\mu \bar{\mu}\gamma_\alpha \mu Z_D^\alpha$$

Model Parameters

- We studied a light vector mediator Z_D with mass $0.01 < M_{ZD} < 2$ GeV and allowed for on-shell as well as off-shell effects in Z_D decay.
- We calculated the width of the Z_D boson including decays to leptonic, hadronic and invisible states.
- We also allowed for an additional invisible decay of Z_D which could arise from Z_D couplings to dark sector particles.

FCNC Processes

1. B_s mixing
2. $B_s \to \mu^+\mu^-$
3. $B \to K^{(*)}\upsilon\bar{\upsilon}$
4. Kaon decay and mixing
5. Radiative $K^+ \to \mu^+\upsilon_\mu Z_D$ decays
6. Radiative $\pi^+ \to \mu^+\upsilon_\mu Z_D$ decays
7. Atomic Parity Violation (APV)
8. Neutrino trident and CEυNS
9. Collider and other bounds (Belle II, W Decay Width, LHCb)



List of Decays for Parameter Fits

Decay	Ref.	q^2 bin (GeV^2)	Measurement	SM expectation
$\frac{d\mathcal{B}}{dq^2}(B^0 \to K^{*0}\mu^+\mu^-) \times 10^8$	[72]	$0.1 - 0.98$	$11.06^{+0.67}_{-0.73} \pm 0.29 \pm 0.69$	10.60 ± 1.54
		$1.1 - 2.5$	$3.26^{+0.32}_{-0.31} \pm 0.10 \pm 0.22$	4.66 ± 0.74
		$2.5 - 4.0$	$3.34^{+0.31}_{-0.33} \pm 0.09 \pm 0.23$	4.49 ± 0.70
		$4.0 - 6.0$	$3.54^{+0.27}_{-0.26} \pm 0.09 \pm 0.24$	5.02 ± 0.75
$\frac{d\mathcal{B}}{dq^2}(B^+ \to K^{*+}\mu^+\mu^-) \times 10^8$	[73]	$0.1 - 2.0$	$5.92^{+1.44}_{-1.30} \pm 0.40$	7.97 ± 1.15
		$2.0 - 4.0$	$5.59^{+1.59}_{-1.44} \pm 0.38$	4.87 ± 0.76
		$4.0 - 6.0$	$2.49^{+1.10}_{-0.96} \pm 0.17$	5.43 ± 0.74
$\frac{d\mathcal{B}}{dq^2}(B^+ \to K^+\mu^+\mu^-) \times 10^8$	[73]	$0.1 - 0.98$	$3.32 \pm 0.18 \pm 0.17$	3.53 ± 0.64
		$1.1 - 2.0$	$2.33 \pm 0.15 \pm 0.12$	3.53 ± 0.58
		$2.0 - 3.0$	$2.82 \pm 0.16 \pm 0.14$	3.51 ± 0.52
		$3.0 - 4.0$	$2.54 \pm 0.15 \pm 0.13$	3.50 ± 0.63
		$4.0 - 5.0$	$2.21 \pm 0.14 \pm 0.11$	3.47 ± 0.60
		$5.0 - 6.0$	$2.31 \pm 0.14 \pm 0.12$	3.45 ± 0.53
$\frac{d\mathcal{B}}{dq^2}(B^0 \to K^0\mu^+\mu^-) \times 10^8$	[73]	$0.1 - 2.0$	$1.22^{+0.59}_{-0.52} \pm 0.06$	3.28 ± 0.52
		$2.0 - 4.0$	$1.87^{+0.55}_{-0.49} \pm 0.09$	3.25 ± 0.56
		$4.0 - 6.0$	$1.73^{+0.53}_{-0.48} \pm 0.09$	3.21 ± 0.54
$\frac{d\mathcal{B}}{dq^2}(B^0_s \to \phi\mu^+\mu^-) \times 10^8$	[74]	$0.1 - 0.98$	$7.74 \pm 0.53 \pm 0.12 \pm 0.37$	11.31 ± 1.34
		$1.1 - 2.5$	$3.15 \pm 0.29 \pm 0.07 \pm 0.15$	5.44 ± 0.61
		$2.5 - 4.0$	$2.34 \pm 0.26 \pm 0.05 \pm 0.11$	5.14 ± 0.73
		$4.0 - 6.0$	$3.11 \pm 0.24 \pm 0.06 \pm 0.15$	5.50 ± 0.69
$\mathcal{B}(B^+ \to K^+e^+e^-) \times 10^8$	[75]	$0.1 - 4.0$	$18.0^{+3.3}_{-3.0} \pm 0.5$	13.73 ± 1.88
		$4.0 - 8.12$	$9.6^{+2.4}_{-2.2} \pm 0.3$	14.11 ± 1.88
$\mathcal{B}(B^0 \to K^{*0}e^+e^-) \times 10^7$	[76]	$0.03^2 - 1.0^2$	$3.1^{+0.9+0.2}_{-0.8-0.3} \pm 0.2$	2.56 ± 0.44
$\mathcal{B}(B \to X_s\mu^+\mu^-) \times 10^6$	[77]	$1.0 - 6.0$	$0.66^{+0.82+0.30}_{-0.76-0.24} \pm 0.07$	1.67 ± 0.15
$\mathcal{B}(B \to X_s e^+e^-) \times 10^6$	[77]	$1.0 - 6.0$	$1.93^{+0.47+0.21}_{-0.45-0.16} \pm 0.18$	1.74 ± 0.16
$\frac{d\mathcal{B}}{dq^2}(B^+ \to K^+e^+e^-) \times 10^9$	[78]	$1.1 - 6.0$	$25.5^{+1.3}_{-1.2} \pm 1.1$	34.9 ± 6.2
$\frac{d\mathcal{B}}{dq^2}(B^0 \to K^{*0}e^+e^-) \times 10^9$	[78]	$1.1 - 6.0$	$33.3^{+2.7}_{-2.6} \pm 2.2$	47.7 ± 7.5

Best Fit Parameter Values

- **Case A:** $M_{Z_D} = 10.07\ \text{MeV}\,, \quad \varepsilon = 1.6 \times 10^{-5}\,, \quad \varepsilon_Z = 0.002$

- **Case B:** $M_{Z_D} = 10.3\ \text{MeV}\,, \quad g_D^{\mu} = 0.28$ at fixed $\varepsilon = 10^{-4}$ and $\varepsilon_z = 10^{-4}$

- **Case C:** $M_{Z_D} = 30.2\ \text{MeV}\,, \quad g_D^{\mu} = 0.033$ at fixed $\varepsilon = 10^{-4}$ and $\varepsilon_z = 10^{-4}$

Results

- Dark photon and dark Z from $U(1)_D$ contribution are studied in $b \longrightarrow s\, l^+ l^-$ observables.
- Constraints on the model parameters were set in different cases:

1. **Case A:** For the base Z_D model,

(a) The parameter space $M_{ZD} < 30$ MeV is excluded primarily by measurements of the proton and cesium weak charges in atomic parity violation experiments.

(b) For $M_{ZD} > 30$ MeV, the mixing parameters are severely constrained by FCNC measurements to which Z_D contributes as a sharp resonance.

2. **Case B:**

(a) The base Z_D model is extended with a direct coupling of Z_D with muons.

(b) The parameter space is restricted to M_{ZD} < 30 MeV. The entire parameter space is ruled out because of enhancements to $K \to \mu\nu X$ and to the W boson width.

3. **Case C:**

(a) In addition to a direct muon coupling, Z_D has a direct coupling to electrons.

(b) This avoids constraints from different sources such as APV. A fit to the $b \to s\mu^+\mu^-$ observables gives a best fit

$$M_{Z_D} = 30.2 \text{ MeV and } g_D^\mu = 0.033 \text{ for } \varepsilon = \varepsilon_Z = 10^{-4}$$

(c) Bounds from neutrino trident production at CCFR, LHCb dark photon searches, W width measurements and $K \to \mu\nu X$ rule out much of the allowed parameter space.

(d) A 2σ region around $100 \leq M_{Z_D} \leq 200\ MeV$ and $0.015 \leq g_D^\mu \leq 0.03$ remains viable.